

Thick Accretion Disk Model for Ultraluminous Supersoft Sources

Wei-Min Gu^{1,4}, Mou-Yuan Sun¹, You-Jun Lu^{2,5}, Feng Yuan^{3,1,4}, and Ji-Feng Liu^{2,5}

ABSTRACT

We propose a geometrically thick, super-Eddington accretion disk model, where an optically thick wind is not necessary, to understand ultraluminous supersoft sources (ULSs). For high mass accretion rates $\dot{M} \gtrsim 30\dot{M}_{\text{Edd}}$ and not small inclination angles $\theta \gtrsim 25^\circ$, where \dot{M}_{Edd} is the Eddington accretion rate, the hard photons from the hot inner region may be shaded by the geometrically thick inner disk, and therefore only the soft photons from the outer thin disk and the outer photosphere of the thick disk can reach the observer. Our model can naturally explain the approximate relation between the typical thermal radius and the thermal temperature, $R_{\text{bb}} \propto T_{\text{bb}}^{-2}$. Moreover, the thick disk model can unify ULSs and normal ultraluminous X-ray sources, where the different observational characteristics are probably related to the inclination angle and the mass accretion rate. By comparing our model with the optically thick outflow model, we find that less mass accretion rate is required in our model.

Subject headings: accretion, accretion disks — black hole physics — X-rays: binaries

1. Introduction

Ultraluminous supersoft sources (ULSs) are a particular group of X-ray binaries, with both a high luminosity of \sim a few 10^{39} erg s⁻¹ and a supersoft thermal spectrum with a peak

¹Department of Astronomy and Institute of Theoretical Physics and Astrophysics, Xiamen University, Xiamen, Fujian 361005, China; guwm@xmu.edu.cn

²Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China

³Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China

⁴SHAO-XMU Joint Center for Astrophysics, Xiamen University, Xiamen, Fujian 361005, China

⁵College of Astronomy and Space Sciences, University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing 100049, China

temperature $\lesssim 0.1$ keV (Di Stefano & Kong 2003). Recently, significant progress has been achieved for two individual ULSs, M101 X-1 and M81 ULS-1. For M101 X-1, Liu et al. (2013) confirmed that the system contains a Wolf-Rayet star and revealed that the orbital period is 8.2 days. Based on this orbital period, they proposed that the black hole probably has a mass around $20 - 30 M_{\odot}$. This is the first time to measure the black hole mass in a ULS by dynamic method. For another ULS, M81 ULS-1, Liu et al. (2015) found blueshifted, broad H α emission lines, which indicate that there exists a relativistic baryonic jet. Moreover, the blueshifted value reveals the inclination angle $\theta < 60^{\circ}$. Consequently, since a white dwarf system is unable to launch such a relativistic jet, the model based on a white dwarf can be ruled out.

Two well-known models for ULSs are related to intermediate-mass black holes (IMBHs) and stellar-mass black holes, respectively. The model based on a standard thin disk (Shakura & Sunyaev 1973) around an IMBH can explain both high bolometric luminosity L_{bol} and low inner disk temperature T_{in} due to the relation $T_{\text{in}} \propto M_{\text{BH}}^{-1/4}$. However, compared with the well-known behaviors of Galactic black hole X-ray binaries (BHXBs), such a model may confront two difficulties. The first one is related to the relative luminosity. Usually, the disk-dominated thermal state of a BHXB occurs for $0.02 L_{\text{Edd}} \lesssim L_{\text{bol}} \lesssim 0.3 L_{\text{Edd}}$ (Maccarone 2003; McClintock et al. 2006), where L_{Edd} is the Eddington luminosity. Such a range corresponds to $0.02 \lesssim \dot{m} \lesssim 0.3$, where $\dot{m} \equiv \dot{M}/\dot{M}_{\text{Edd}}$ is the dimensionless mass accretion rate, and \dot{M}_{Edd} is the Eddington accretion rate defined as $L_{\text{Edd}}/(\eta c^2)$. In the present work we choose $\eta = 1/16$ corresponding to the well-known Paczyński-Wiita potential (Paczyński & Wiita 1980). For the IMBH model, however, the relative luminosity $L_{\text{bol}}/L_{\text{Edd}}$ is generally far below the lower limit 0.02. The second difficulty is related to the relativistic jet. The existence of jet in M81 ULS-1 indicates that the jet may be a common phenomenon in ULSs. In Galactic BHXBs, there exist two types of jets, i.e., the steady jet in the low/hard state, and the episodic jet during the transition between low/hard state and high/soft state (Fender et al. 2004). However, a standard thin disk around an IMBH should correspond to a purely soft state, which disagrees with the conditions for the above two types of jets. Thus, the IMBH model can be ruled out.

The other model, which is based on a stellar-mass black hole, may also confront difficulties. First, for such a black hole, the accretion rate ought to be around or super Eddington due to the high luminosity. In our Galaxy, however, such a supersoft spectrum has never been found among the around twenty identified BHXBs, some of which are likely to achieve or above Eddington luminosity such as GRS 1915+105. Second, many ultraluminous X-ray sources (ULXs) have been found in nearby galaxies, most of which are believed to be stellar-mass black holes with super-Eddington accretion (for a review, see Feng & Soria 2011). If ULSs are in the same scenario, then a question will arise: how can the super-Eddington

accretion around stellar-mass black hole show the apparently different radiation characteristics?

In this *Letter*, we will propose a new model to understand ULSs, and try to unify ULSs and ULXs in the same frame. The remainder of this *Letter* is organized as follows. The thick accretion disk model is proposed in Section 2. Application of such a model to ULSs is presented in Section 3. Conclusions and discussion are made in Section 4.

2. Thick disk model

As mentioned in the previous section, ULSs are likely to be powered by super-Eddington accretion around stellar-mass black holes. The classic model for super-Eddington accretion is the slim disk (Abramowicz et al. 1988). The half-thickness H of slim disks approaches the radius R , which are geometrically much thicker than the standard thin disks. Recent simulations have made great progress on the super-Eddington accretion process, including the identification of an important new energy transport mechanism in addition to the diffusion, i.e., the vertical advection of radiation (Jiang et al. 2014; Sądowski & Narayan 2015b), the radiation-powered baryonic jet (Sądowski & Narayan 2015a), the strongly anisotropic feature of radiation (Sądowski & Narayan 2015b; Narayan et al. 2015), and the presence of strong wind (Ohsuga & Mineshige 2011; Yang et al. 2014; Sądowski & Narayan 2015a,b; Moller & Sądowski 2015). In addition, such simulations showed that the disk is geometrically thick, i.e., the opening angle between the photosphere and the equatorial plane is quite large. For example, Narayan et al. (2015) made global simulations for the case $\dot{m} = 11$ and showed a geometrically thick accretion disk, where the polar angle of the photosphere is around 25° . As a consequence, the inner disk will be invisible to an observer with an inclination angle $\theta \gtrsim 25^\circ$. On the other hand, some analytic works also pointed out that the super-Eddington accretion disk, which is optically thick and probably advection dominated, is likely to be geometrically thick rather than slim if the gravitational force of the central black hole is well treated (Gu & Lu 2007; Gu et al. 2009; Gu 2012).

In the present work, we propose a geometrically thick, super-Eddington accretion model for ULSs, where the hot inner disk can be shaded and the hard photons from this part cannot be observed if the inclination angle is not small. The high bolometric luminosity and the low thermal temperature of ULSs suggest a large photosphere radius, $R_{\text{bb}} \gtrsim 100R_{\text{g}}$, where $R_{\text{g}} \equiv 2GM_{\text{BH}}/c^2$ is the Schwarzschild radius. Thus, the mass accretion rate ought to be extremely high such that the flow can have a geometrically thick inner disk extended to $\gtrsim 100R_{\text{g}}$. In this scenario, there are two necessary conditions for ULSs, i.e., high mass accretion rates and not small inclination angles. We would stress that a basic assumption in

our model is that an optically thick wind does not exist, which is unnecessary to explain the observational properties of ULSs. A cartoon picture of such a model, which includes ULSs and ULXs, is shown in Figure 1. It is seen from this figure that the accretion disk can be separated into two parts by a typical transition radius R_{tr} , i.e., an inner thick disk ($R \lesssim R_{\text{tr}}$) and an outer thin disk ($R \gtrsim R_{\text{tr}}$). In the classic theory for super-Eddington accretion, there exists a transition radius which connects an inner slim disk and an outer thin disk (e.g., Abramowicz et al. 1988; Watarai et al. 2000). As mentioned in the previous paragraph, for the super-Eddington accretion case, the inner disk is more likely to be geometrically thick rather than slim. That is why we propose a thick inner disk here. In addition, the system may have a baryonic jet as revealed by Liu et al. (2015). Such a baryonic jet was also found in simulations with a relativistic speed $\sim 0.3c$ (Sądowski & Narayan 2015a). Since the jet can extend to a large distance, it may be observed even for large inclination angles. For the individual source M81 ULS-1, as mentioned in the first section, the blueshifted $\text{H}\alpha$ emission lines indicate that the inclination angle ought to be $\theta < 60^\circ$.

On the contrary, for a small inclination angle, an observer is able to see the hard photons from the inner disk. Moreover, according to the simulation results (e.g., Figure 17 of Narayan et al. 2015), the isotropic equivalent luminosity can be far beyond the Eddington one ($\sim 10L_{\text{Edd}}$ for $\theta < 25^\circ$, as shown by the filled red circles in their Figure 17). Thus, a super-Eddington accreting stellar-mass black hole may appear as a normal ULX to the observer with small inclination angles, as illustrated by Figure 1.

It is known that the spin of stellar-mass black hole can be measured through the X-ray continuum-fitting method (Zhang et al. 1997), which is based on the standard thin disk theory. However, McClintock et al. (2006) found that the spin parameter a_* of GRS 1915+105 decreases for high luminosity $L \gtrsim 0.3L_{\text{Edd}}$. Obviously, the value of a_* cannot have significant change in a relatively short timescale. The reason is that the inner radius R_{in} moves outward for $L \gtrsim 0.3L_{\text{Edd}}$, and therefore it is larger than the radius of the innermost stable circular orbit R_{ISCO} . A possible physical explanation is that the disk will inflate for $L \gtrsim 0.3L_{\text{Edd}}$ and therefore the innermost region may be shaded (McClintock et al. 2006). We would stress that such outward moving R_{in} above $0.3L_{\text{Edd}}$ is not a unique phenomenon for GRS 1915+105, which is verified as a near extreme Kerr black hole. For another BHXB LMC X-3 with low spin (Steiner et al. 2014), it was also found that R_{in} moves outward for $L \gtrsim 0.3L_{\text{Edd}}$ (Steiner et al. 2010). Even with a new spectral model “slimbb”, which is based on theoretical works on slim disks (e.g., Sądowski et al. 2011) and the energy advection is taken into account, R_{in} still moves outward beyond $0.3L_{\text{Edd}}$ (Straub et al. 2011). In our opinion, the theoretical work (Sądowski et al. 2011) has achieved great progress on the slim disk model, but may not be so accurate due to the approximate vertical component of the gravitational force. As discussed in Gu (2012), if the gravitational force is well treated (such

as using the spherical coordinates), the inner disk will be much thicker, which may provide a clue to solve the inconsistent a_* problem. Moreover, the outward moving R_{in} was also found in neutron star X-ray binaries (e.g., XTE J1701-462, Weng & Zhang 2011) and ULXs (e.g., NGC 1313 X-2, Weng et al. 2014). Thus, we can regard $0.3L_{\text{Edd}}$ as a general upper limit luminosity for the standard thin disk, beyond which such a model may be invalid.

Previous theoretical works (e.g., Watarai et al. 2000; Kato et al. 2008) showed that the typical transition radius R_{tr} is proportional to \dot{m} , we therefore assume the following equation:

$$R_{\text{tr}} = \lambda \dot{m} R_{\text{g}} , \quad (1)$$

where λ is a dimensionless parameter. The value of λ can be estimated as follows. For a non-spinning black hole, we can regard $R_{\text{ISCO}} = 3R_{\text{g}}$ as the inner radius for luminosity below the critical value $0.3L_{\text{Edd}}$, which corresponds to $\dot{m} = 0.3$. Beyond the critical value the inner radius will start to move outward. Thus, $\lambda \sim 10$ may be a good choice since it can match the above equation ($R_{\text{tr}} = R_{\text{ISCO}}$) at the critical point $\dot{m} = 0.3$. We therefore adopt $\lambda = 10$ for the following analyses.

For a large inclination angle, since the inner disk is invisible, the luminosity from the outer thin disk ($R \gtrsim R_{\text{tr}}$) can be derived as

$$L_{\text{disk}}^{\text{thin}} \approx \int_{R_{\text{tr}}}^{\infty} \frac{3GM_{\text{BH}}\dot{M}}{8\pi R^3} \cdot 4\pi R dR = 1.2L_{\text{Edd}} . \quad (2)$$

It is interesting that the above equation implies that $L_{\text{disk}}^{\text{thin}}$ is independent of \dot{m} .

As shown by Figure 1, apart from the outer thin disk, the radiation from the outer photosphere of the thick disk also has contribution to the total luminosity for a large inclination angle. Since the radiative force should be less than gravitational force at the photosphere, we may roughly assume that the former balances half of the latter, i.e., $L_{\text{disk}}^{\text{thick}} \sim 0.5L_{\text{Edd}}$. Both $L_{\text{disk}}^{\text{thin}}$ and $L_{\text{disk}}^{\text{thick}}$ are the thermal radiation, so we may simply calculate the total bolometric luminosity as

$$L_{\text{bol}} \approx L_{\text{disk}}^{\text{thin}} + L_{\text{disk}}^{\text{thick}} = 1.7L_{\text{Edd}} , \quad (3)$$

which is also independent of \dot{m} . We would stress that, even for the extreme value of $L_{\text{disk}}^{\text{thick}}$ such as 0 or L_{Edd} , the variation of the total bolometric luminosity L_{bol} is less than 30%, which will not have essential influence on the present results.

The typical blackbody radius R_{bb} and temperature T_{bb} should match the relation:

$$L_{\text{bol}} = 4\pi R_{\text{bb}}^2 \sigma T_{\text{bb}}^4 . \quad (4)$$

Equation (3) implies a saturation of L_{bol} for a certain ULS. We therefore directly obtain the relation $R_{\text{bb}} \propto T_{\text{bb}}^{-2}$ by Equation (4) for varying accretion rates. Such a relation is in

good agreement with the observational data, as revealed by Urquhart & Soria (2015). More interestingly, Equation (3) indicates $L_{\text{bol}} \propto M_{\text{BH}}$, which suggests that the central black hole mass can simply be estimated by the luminosity. For the particular ULS M101 X-1, which is the unique source with dynamic measurement, the black hole mass can be estimated by the luminosity $L_{\text{bol}} \approx 5 \times 10^{39} \text{ erg s}^{-1}$ and thus $M_{\text{BH}} \approx 23M_{\odot}$, which agrees with the dynamic result, i.e., probably $20\text{--}30M_{\odot}$ (Liu et al. 2013).

A unified description of ULSs, normal ULXs, and BHXBs is shown in Figure 2, which is based on stellar-mass black hole systems. Galactic BHXBs are generally below the Eddington luminosity. According to our model, there are two necessary conditions for ULSs to appear, which are high accretion rates $\dot{m} \gtrsim 30$ and not small inclination angles $\theta \gtrsim 25^\circ$. For the other cases with super-Eddington accretion, i.e., either small inclination angles $\theta \lesssim 25^\circ$ or moderate super-Eddington accretion $1 \lesssim \dot{m} \lesssim 30$, since the hot inner disk is visible to the observer and the isotropic equivalent luminosity is beyond the Eddington one, the sources are likely to appear as normal ULXs. We would stress that, even though ULSs have a wider range for the inclination angle ($\theta \gtrsim 25^\circ$) than ULXs ($\theta \lesssim 25^\circ$), the required mass accretion rate is much more critical for ULSs ($\dot{m} \gtrsim 30$) than for ULXs ($\dot{m} \gtrsim 1$). Thus, it is reasonable that we have found hundreds of ULXs whereas only several ULSs.

3. Application to ULSs

The transition radius R_{tr} may be roughly regarded as the typical blackbody radius, i.e., $R_{\text{tr}} \approx R_{\text{bb}}$. This is the location where the photosphere of the inner quasi-spherical part touches the equatorial plane. By combining Equations (1), (3) and (4) we can derive the expression of kT_{bb} as

$$kT_{\text{bb}} \approx 660 \dot{m}^{-\frac{1}{2}} \left(\frac{M_{\text{BH}}}{10M_{\odot}} \right)^{-\frac{1}{4}} \text{ eV} . \quad (5)$$

Our analytic results (solid and dashed lines) together with the observations (symbols) are shown in Figure 3. The two horizontal blue dashed lines correspond to fixed black hole masses, $M_{\text{BH}} = 3M_{\odot}$ and $30M_{\odot}$, which are based on Equation (3). The two inclined red solid lines correspond to fixed accretion rates $\dot{m} = 30$ and 100 , which are derived by combining Equations (3) and (5). The symbols represent observational results of a set of seven ULSs, which are taken from Table 2 of Urquhart & Soria (2015). It is seen from Figure 3 that most of the symbols locate between the two blue dashed lines and also between the two red solid lines, i.e., in the range $3M_{\odot} \lesssim M_{\text{BH}} \lesssim 30M_{\odot}$ and $30 \lesssim \dot{m} \lesssim 100$, which indicates a stellar-mass black hole with extremely high accretion rates.

As mentioned in the first section, the radiation characteristic of ULSs challenges the clas-

sic accretion theory. Both simulations (e.g., Ohsuga & Mineshige 2011; Sądowski & Narayan 2015a) and analytic studies (e.g., Gu 2012, 2015) showed that outflows are significant in super-Eddington accretion flows. Another possible mechanism for ULs is the optically thick outflow model, which was first introduced by King & Pounds (2003) and was developed and applied to M101 X-1 by Shen et al. (2015). Recently, Soria & Kong (2015) and Urquhart & Soria (2015) investigated such an issue in more details based on the observational data from *Chandra* and *XMM-Newton*. It is interesting that, despite the completely different models, the analytic results are similar between the outflow model and ours. For instance, Equations (24-25) of Soria & Kong (2015) also imply that the total luminosity is roughly independent of \dot{m} , and is proportional to the black hole mass. As a consequence, their blue solid lines in the right two panels of Figure 9 (Soria & Kong 2015), which correspond to fixed black hole masses, are nearly horizontal as shown in our Figure 3 (blue dashed lines).

For more detailed comparison, we find that the required mass accretion rate in our model is significantly less than that in the outflow model. For example, for the source M101 X-1, their Figure 9 (Soria & Kong 2015) indicates $\dot{m} \gtrsim 1000$, whereas in our model the accretion rate is probably in the range $30 \lesssim \dot{m} \lesssim 100$, as shown in Figure 3. In addition, we would stress that the essential difference from the outflow model is that an optically thick wind is not necessary in our model to explain the observational properties of ULs. For the case that a strong optically thick wind exists, the transition radius may be located much further away, i.e., $R'_{\text{tr}} \gg R_{\text{tr}}$, whereas the effect on the total bolometric luminosity may be quite weak (L_{bol} may stay close to L_{Edd}). As a consequence, for a given pair of the observational L_{bol} and T_{bb} (R_{bb} can therefore be derived by Equation (4)), the required \dot{m} in our model may be even lower due to the relations $R_{\text{tr}} \propto \dot{m}$ (Equation (1)) and probably $R_{\text{bb}} \gg R_{\text{tr}}$.

4. Conclusions and discussion

In this *Letter*, we have proposed a geometrically thick accretion disk model to understand ULs. In our opinion, such a model can unify ULs and most ULXs under the scenario of a stellar-mass black hole with super-Eddington accretion. There are two necessary conditions for ULs, i.e., high mass accretion rates $\dot{m} \gtrsim 30$ and not small inclination angles $\theta \gtrsim 25^\circ$. For the other cases with super-Eddington accretion, the sources are likely to appear as normal ULXs. Our model can naturally explain the observational relation $R_{\text{bb}} \propto T_{\text{bb}}^{-2}$ for ULs. In addition, we suggest that the black hole mass in ULs can be estimated simply from the total bolometric luminosity. By comparing our model with the optically thick outflow model, we find that less mass accretion rate is required in our model.

We would point out that there exists uncertainty for the value of λ in Equation (1). In the present work we adopt $\lambda = 10$ according to previous works on black hole spin measurement. From the theoretical point of view, Watarai et al. (2000) implies $\lambda \sim 2.4$ due to their result $R_{\text{tr}} \approx R_{\text{in}}$ for $\dot{m} = 1.25$ (note that there exists different definition of \dot{m} , thus their $\dot{m} = 20$ is equivalent to our $\dot{m} = 1.25$). Since their analyses are based on a Taylor Expansion of the vertical component of the gravitational force, which is probably magnified particularly for geometrically not thin disks (Gu & Lu 2007; Gu 2012), the geometrically thickness may be underestimated and therefore the real value of R_{tr} may be larger. Actually, Gu (2012) investigated this issue in spherical coordinates in order to avoid the approximation of gravity, and found that the disk can be geometrically thick at $10R_{\text{g}}$ for $\dot{m} = 0.6$, which corresponds to $\lambda \approx 17$ from Equation (1). Considering the Newtonian potential was adopted in Gu (2012) and therefore the viscous heating rate has been enlarged, λ should be less than 17. With regard to the theoretical range $2.4 < \lambda < 17$, it may be a reasonable assumption for $\lambda = 10$. Nevertheless, variation of λ by a small factor will have only slight quantitative influence on the present results.

Our model is based on the stellar-mass black hole system. For ULXs, however, we should mention the other two possibilities. One possibility is neutron star X-ray binaries such as M82 X-2 (Bachetti et al. 2014). The other one may be IMBH systems, particularly for those sources with extremely high luminosity $L \gtrsim 10^{41} \text{ erg s}^{-1}$, such as ESO 243-49 HLX-1 (Farrell et al. 2009).

As discussed in Section 2, the relation $L_{\text{bol}} \approx 1.7L_{\text{Edd}}$ may be used to estimate the black hole mass in ULXs. Although the inclination angle may have influence on the apparent luminosity, the variation should not be essential due to the limit range of the angle. Moreover, such a relation indicates a saturated bolometric luminosity for ULXs, or even more general, for super-Eddington accretion in different scale. In this scenario, for super-massive black holes in active galactic nuclei, if mass supply is sufficient, a similar supersoft state may be found. If this is the case, such system may be regarded as another type of “Standard Candle” and will have potential application to the study of cosmology.

The authors thank Shan-Shan Weng for beneficial discussions, and the referee for constructive comments that improved the *Letter*. This work was supported by the National Basic Research Program of China (973 Program) under grants 2014CB845800 and 2014CB845705, the National Natural Science Foundation of China under grants 11573023, 11333004, 11373031, 11133005, 11573051, 11425313 and 11222328, the CAS/SAFEA International Partnership Program for Creative Research Teams, and the Fundamental Research Funds for the Central Universities under grant 20720140532.

REFERENCES

- Abramowicz, M. A., Czerny, B., Lasota, J.-P., & Szuszkiewicz, E. 1988, *ApJ*, 332, 646
- Bachetti, M., Harrison, F. A., Walton, D. J., et al. 2014, *Nature*, 514, 202
- Di Stefano, R., & Kong, A. K. H. 2003, *ApJ*, 592, 884
- Farrell, S. A., Webb, N. A., Barret, D., Godet, O., & Rodrigues, J. M. 2009, *Nature*, 460, 73
- Fender, R. P., Belloni, T. M., & Gallo, E. 2004, *MNRAS*, 355, 1105
- Feng, H., & Soria, R. 2011, *New A Rev.*, 55, 166
- Gu, W.-M. 2012, *ApJ*, 753, 118
- Gu, W.-M. 2015, *ApJ*, 799, 71
- Gu, W.-M., & Lu, J.-F. 2007, *ApJ*, 660, 541
- Gu, W.-M., Xue, L., Liu, T., & Lu, J.-F. 2009, *PASJ*, 61, 1313
- Jiang, Y.-F., Stone, J. M., & Davis, S. W. 2014, *ApJ*, 796, 106
- Kato, S., Fukue, J., & Mineshige, S. 2008, *Black-Hole Accretion Disks: Towards a New Paradigm* (Kyoto: Kyoto Univ. Press)
- King, A. R., & Pounds, K. A. 2003, *MNRAS*, 345, 657
- Liu, J.-F., Bregman, J. N., Bai, Y., Justham, S., & Crowther, P. 2013, *Nature*, 503, 500
- Liu, J.-F., Bai, Y., Wang, S., et al. 2015, *Nature*, 528, 108
- Maccarone, T. J. 2003, *A&A*, 409, 697
- McClintock, J. E., Shafee, R., Narayan, R., et al. 2006, *ApJ*, 652, 518
- Moller, A., & Sadowski, A. 2015, *arXiv:1509.06644*
- Narayan, R., Zhu, Y., Psaltis, D., & Sądowski, A. 2015, *arXiv:1510.04208*
- Ohsuga, K., & Mineshige, S. 2011, *ApJ*, 736, 2
- Paczynsky, B., & Wiita, P. J. 1980, *A&A*, 88, 23
- Sądowski, A., Abramowicz, M., Bursa, M., et al. 2011, *A&A*, 527, A17

- Sądowski, A., & Narayan, R. 2015a, MNRAS, 453, 3213
- Sądowski, A., & Narayan, R. 2015b, arXiv:1509.03168
- Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
- Shen, R.-F., Barniol Duran, R., Nakar, E., & Piran, T. 2015, MNRAS, 447, L60
- Soria, R., & Kong, A. K. H. 2015, arXiv:1511.04797
- Steiner, J. F., McClintock, J. E., Orosz, J. A., et al. 2014, ApJ, 793, L29
- Steiner, J. F., McClintock, J. E., Remillard, R. A., et al. 2010, ApJ, 718, L117
- Straub, O., Bursa, M., Sądowski, A., et al. 2011, A&A, 533, A67
- Urquhart, R., & Soria, R. 2015, arXiv:1511.05275
- Watarai, K.-y., Fukue, J., Takeuchi, M., & Mineshige, S. 2000, PASJ, 52, 133
- Weng, S.-S., & Zhang, S.-N. 2011, ApJ, 739, 42
- Weng, S.-S., Zhang, S.-N., & Zhao, H.-H. 2014, ApJ, 780, 147
- Yang, X.-H., Yuan, F., Ohsuga, K., & Bu, D.-F. 2014, ApJ, 780, 79
- Zhang, S. N., Cui, W., & Chen, W. 1997, ApJ, 482, L155

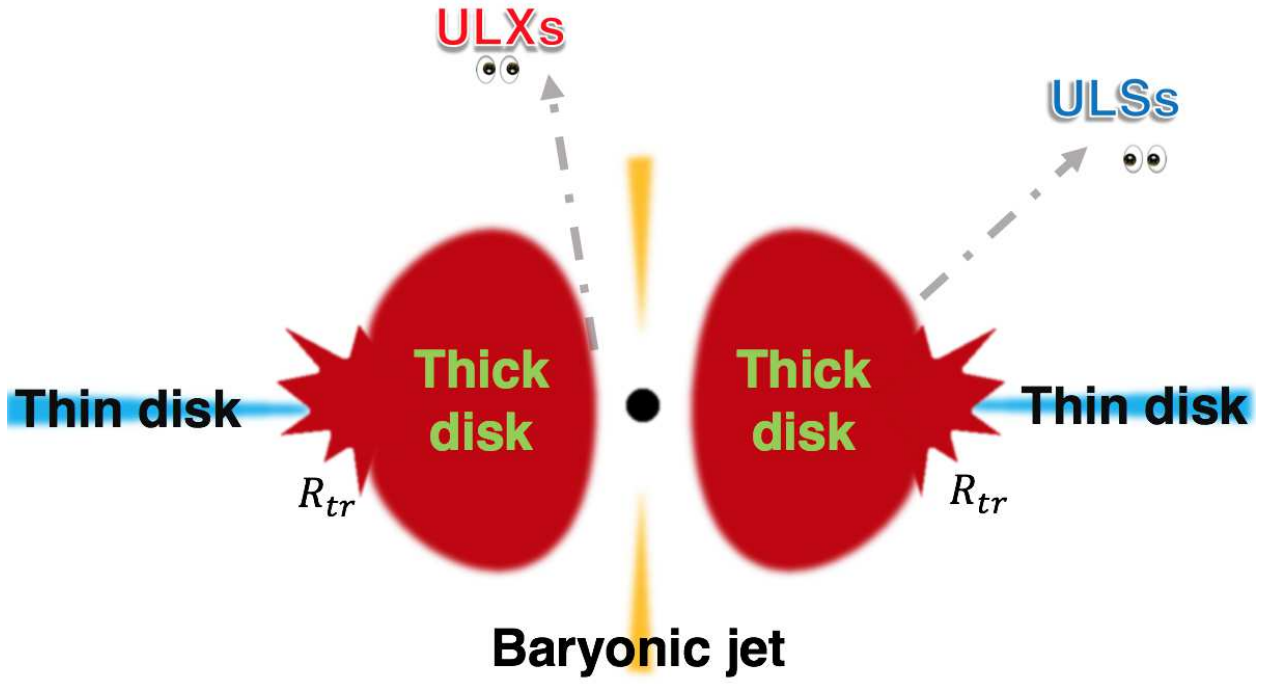


Fig. 1.— A cartoon picture of super-Eddington accretion around stellar-mass black holes for $\dot{m} \gtrsim 30$, which shows ULXs and normal ULSs with different inclination angles.

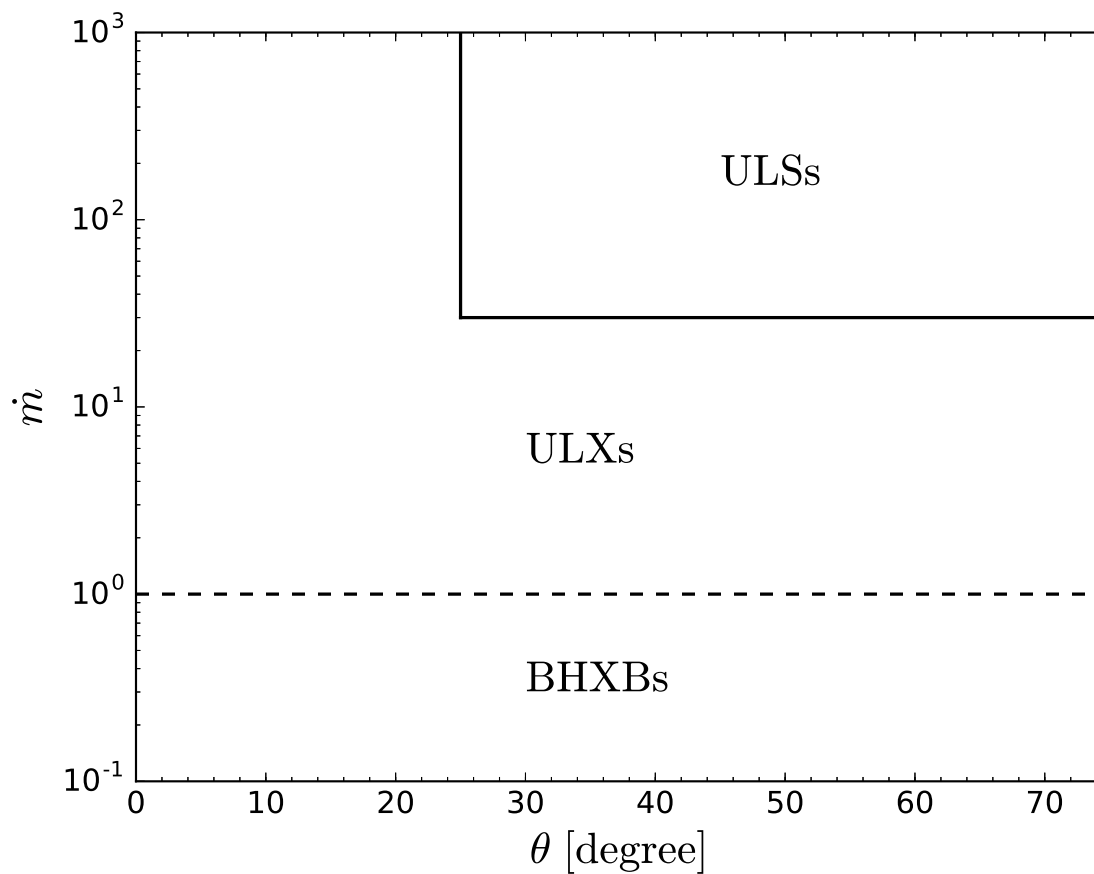


Fig. 2.— A unified description of ULSs, normal ULXs, and BHXBs based on stellar-mass black hole systems. BHXBs in our Galaxy are generally below the Eddington luminosity. ULSs will appear for both high accretion rates $\dot{m} \gtrsim 30$ and not small inclination angles $\theta \gtrsim 25^\circ$. For the other cases with super-Eddington accretion, the sources are likely to be normal ULXs.

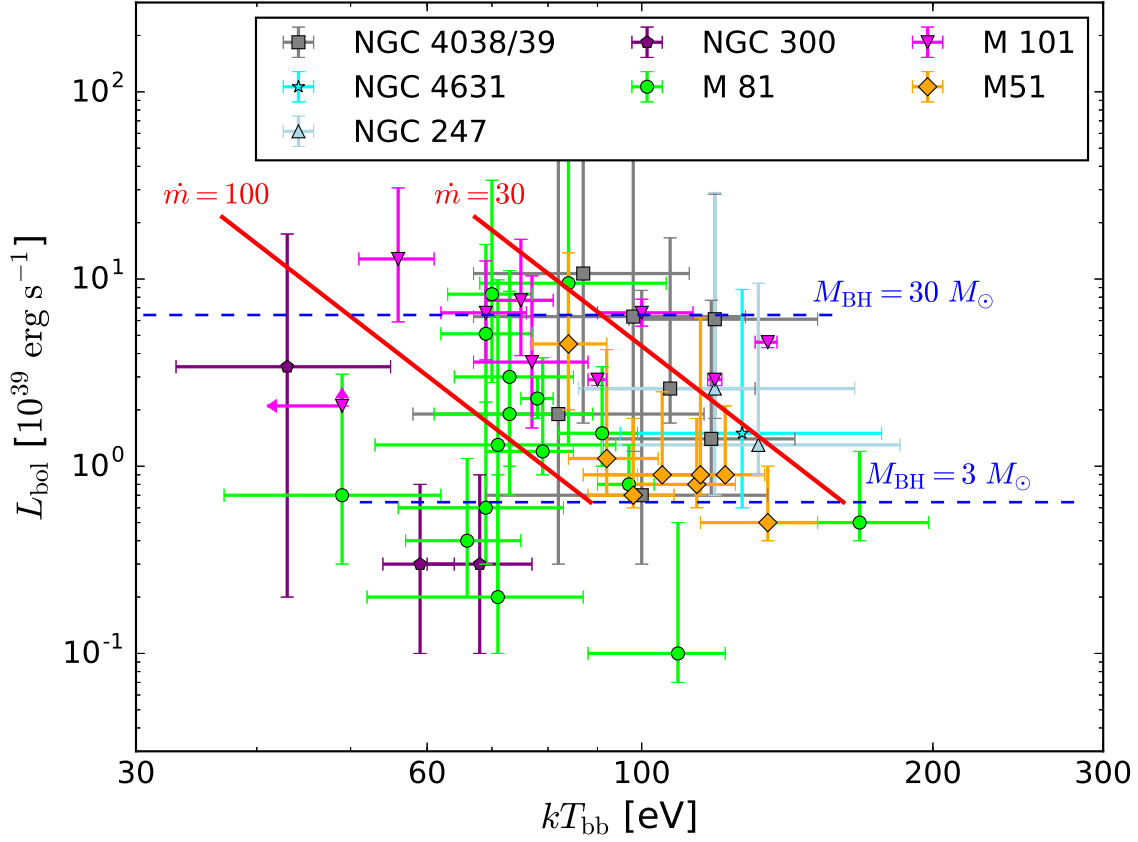


Fig. 3.— Comparison of the observations (symbols) with our analytic results (solid and dashed lines) for ULSs in $L_{\text{bol}} - kT_{\text{bb}}$ diagram. The symbols represent seven ULSs, which are taken from Table 2 of Urquhart & Soria (2015). The horizontal blue dashed lines correspond to fixed black hole masses, and the inclined red solid lines correspond to fixed mass accretion rates.